OFIS EXPERIMENTS AT CAMP ELLIOTT: PAVING THE WAY TO INFRASONIC RADAR AND A PORTABLE INFRASONIC SENSOR CALIBRATOR

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ABSTRACT

Optical fiber infrasound sensors (OFIS) are long compliant tubes wrapped with two optical fibers that integrate pressure variation along the length of the tubes via laser interferometry at the speed of light. We have previously shown that several OFIS arms can resolve the back azimuth and elevation angle of infrasound signals due to the spectral fingerprint of the instrument response in the recorded signal and the time separation provided by separating the centers of each OFIS arm. In this paper, we present the recent results of calibration, coherence, wind-noise reduction, and fine-tuning experiments that we accomplished in route to completing our grant objectives. Specifically, we show that the sensitivity of the OFIS is temperature dependent, and develop a real-time calibration system that allows us to compensate for this variation. We also show that M-sequences transmitted via subwoofers can be used as portable calibration tools in the low-frequency audible range and can test wind noise reduction technologies for some sensors. Comparison of a 60-m OFIS with a B&K microphone at a signal frequency of 50 Hz for a source ~300 m away shows that the OFIS reduces wind and other types of undesirable noise by 12 dB over the B&K microphone with an attached sponge wind filter. We also present the layout of a six-arm OFIS array at Camp Elliott (CEL) in north San Diego county where our investigations are continuing. This array has an aperture of 150 m, and is collocated with a digital video camera that will provide confirmation of the back azimuth and elevation angle of aircraft infrasound signals that are tracked by a passive infrasonic radar system.

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OBJECTIVES

The overall objective of this research is to use the high precision provided by laser interferometry to reliably record minute infrasonic signals in the presence of detrimental wind noise. Specifically, we are further developing the OFIS, which is a silicone tube wrapped with two fibers that integrates the pressure variation along the length of the tube in an effort to stack the coherent signal while attenuating incoherent wind noise (Fig. 1). We have previously shown evidence that the OFIS has a lower noise floor than traditional pipe-arrays in low-wind conditions from 1-10 Hz (Zumberge et al., 2003). We are also developing techniques that take advantage of the averaging and tuning properties of the OFIS to measure signal orientation parameters (e.g., phase velocity direction). Because an OFIS array typically occupies less space than traditional mechanical wind filters (Fig. 2), we seek to find the optimum configuration of an OFIS array that minimizes the occupied space while maximizing the signal back azimuth resolution.

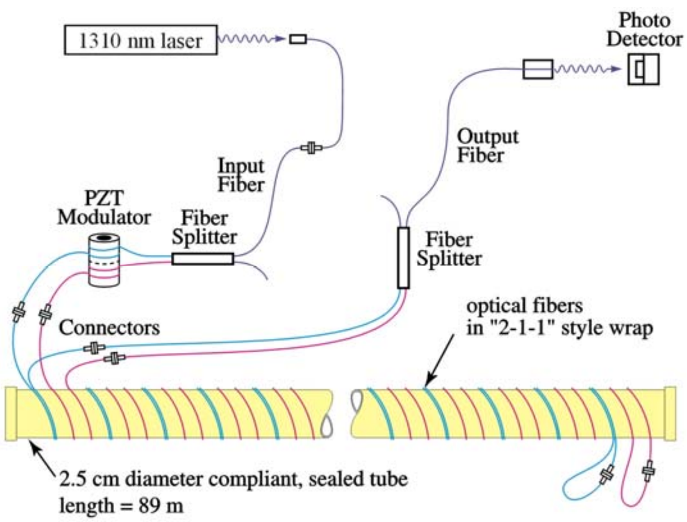


Fig. 1. Schematic of one of six Optical Fiber Infrasound Sensor (OFIS) arms that are operating at Camp Elliott (CEL) in north San Diego county.

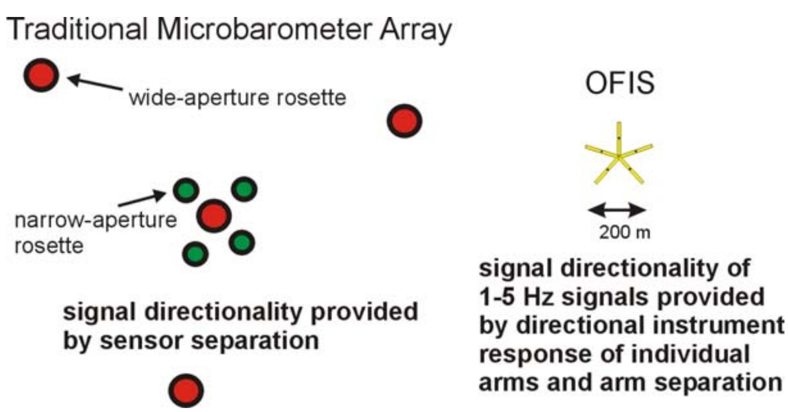


Fig. 2. A typical 8-element infrasound array (left) and a 5-arm OFIS on the right. Rosettes are spatial filters created by an array of inlets connected to underground pipes that all connect to a centrally located microbarometer.

The specific objective of this research that we report on here is to develop a new, generic infrasound calibration tool using M-sequence methodologies and to develop a real-time OFIS infrasonic radar system with which we can directly compare to real-time sky video in the tracking of certain aircraft.

RESEARCH ACCOMPLISHED

Camp Elliott OFIS Array

We deployed four parallel, 60-m OFIS at Camp Elliott (CEL), in north San Diego county near Miramar USMC Air Station in the late spring of 2006. During the summer of 2007, we installed a six-arm OFIS at CEL (Fig. 3). Each arm is 60 m long and located on the surface. The central element is a circular OFIS with a 7 m diameter. A weather station, a five megapixel video camera, and a B&K microphone with sponge wind filter were also installed. The OFIS arms may also be buried beneath about 4 in of coarse gravel during the autumn of 2007.

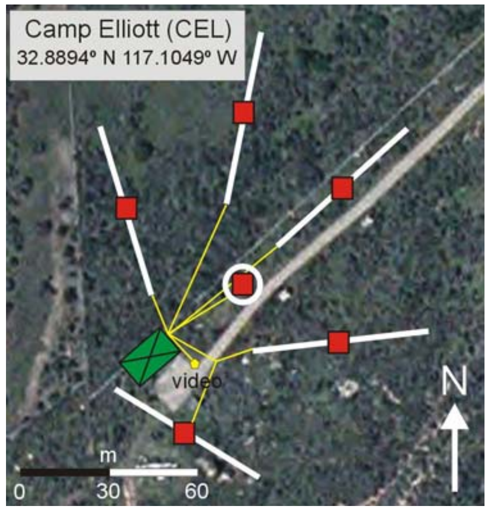


Fig. 3. 2007 Camp Elliott OFIS array collocated with an all-sky digital video camera to use as ground truth for the real-time infrasonic radar system.

Obstacles and Objective-Related Accomplishments

The OFIS performed well during the WSMR II experiment in the spring of 2006. The signal-to-noise ratio was comparable to most the collocated porous-hose Chaparral elements that did not have obvious noise problems (of an unknown origin). However, we observed some minor, but anomalous rocket signal amplitudes with four 60-m OFIS arms. At Camp Elliott (CEL) we laid out these OFIS arms within a few inches of each other parallel to the strain meter to further investigate this (Fig. 3). We also made similar anomalous amplitude observations when we investigated this at Pinion Flats Observatory (PFO) during a comparison between a short (30 m) and long (180 m) OFIS in November 2006. One of our findings resulted in a new feature to the OFIS—a real-time calibration system that is analogous to using predictable ubiquitous Earth tides in seismometer calibration.

Differential Optical Path Lengths

The laser beam is split into two fibers that are wrapped around the OFIS (Fig. 1). At the end of these two fibers, they are recombined to form a fringe signal (x) that is measured by a photo detector. A piezo-electric crystal that is wrapped by one of the two fibers, is driven by a 156 kHz oscillator. This oscillator also drives a lock-in amplifier that measures the derivative (y) of the fringe signal with respect to a change in the optical path length difference. A pressure change therefore traces out an ellipse of some geometry in x/y space (in Volts). A least-squares inversion is applied to the x/y data in real time to obtain the ellipse parameters, which are used to obtain the phase angle (and pressure change) along the ellipse for every x/y point in real-time. The time window that is used to obtain the ellipse parameters is typically the last 25 seconds of recorded data.

The two optical fibers comprising the Mach-Zender interferometer need to be about the same length for the type of laser used in order to establish a reliable ellipse for a given pressure signal. However, we did not know precisely how close their lengths needed to match before the interferometer was impacted detrimentally by optical noise. To quantify this, four different lengths of fiber were connected in various ways to the fibers wrapped around an OFIS to create about 20 different differential fiber lengths. For each case, we determined the best-fitting ellipse, then

calculated the ellipse-radius-normalized RMS distance between the ellipse and the data points (Fig. 4). We expect for a differential fiber length of 0 to be a nearly perfect match (RMS=0). We found that the ellipse begins to become detrimentally affected when the differential fiber length exceeds about 7 inches. Consequently, we trimmed all the fibers on our OFIS arms such that the differential fiber lengths are less than 2 inches.

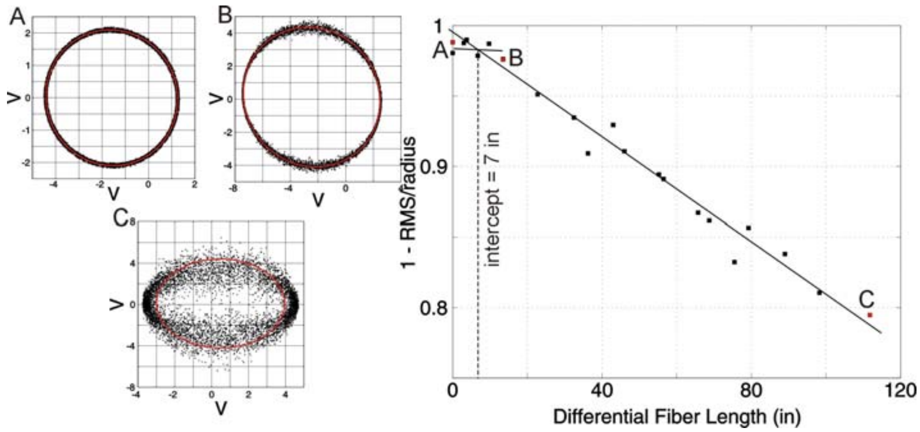


Fig. 4. Determining the relationship between optical noise and differential fiber length.

Polarization Change and White Socks

The ellipse size and geometry is one factor in the OFIS sensitivity. Ideally, we would like a circle that maximizes the range on the A/D converters (+/- 10 V in x/y space). A minor issue that affects uptime is polarization change in the fibers wrapped around the OFIS. Polarization change is strongly correlated with temperature variations of the sensor (due to silicone expansion/contraction and temperature change of the fiber itself). Although this can be circumvented easily by using a diversity detector, a more elegant solution is preferred since a diversity detector requires at least twice the amount of optical/electrical components in the data recording system. Ignoring polarization change can lead to down times of up to ~10% of the time (greatly depends on environmental conditions).

The silicone tube is wrapped with insulation and placed inside 4 inch diameter, perforated black drainage tube (Fig. 5a). This tube can absorb a lot heat from the sun, which can contribute to large internal temperature variations and polarization change. To minimize this, we performed an experiment by splitting PVC pipe along its length, and laying it on top of the OFIS. Our preliminary results suggested that the PVC does very well in reducing polarization change. However, it also seemed to reduce the amplitude of the infrasound signals observed, and they are difficult to keep stationary in wind (which can also lead to an increase in noise as the PVC repeatedly impacts the underlying OFIS).

We performed another experiment by installing a white exterior mesh shield over the OFIS (Fig. 5b). This also seems to have reduced the temperature/polarization change while at the same time eliminating the problems inherent in the PVC pipe approach. Figure 5c shows the x/y data for the leftmost OFIS (Fig. 5a w/o the white shield) in 4 minute time bins beginning at 8:00 AM local time. From 8:00 to noon the temperature increases gradually from 59º to 77º F (18º change) and the ellipse changes its geometry and almost collapses twice. Figure 5d shows the x/y data for the same OFIS but with the white shield (Fig. 5b) on a different day. The temperature ranges from 61º to 85º (24º change), and the ellipses do not change as much. We have adopted this shield as part of the OFIS fabrication routine. Although the shields do not eliminate polarization change, an OFIS buried under ~4 in of coarse gravel or a thermally controlled OFIS does not experience polarization change (100% uptime).

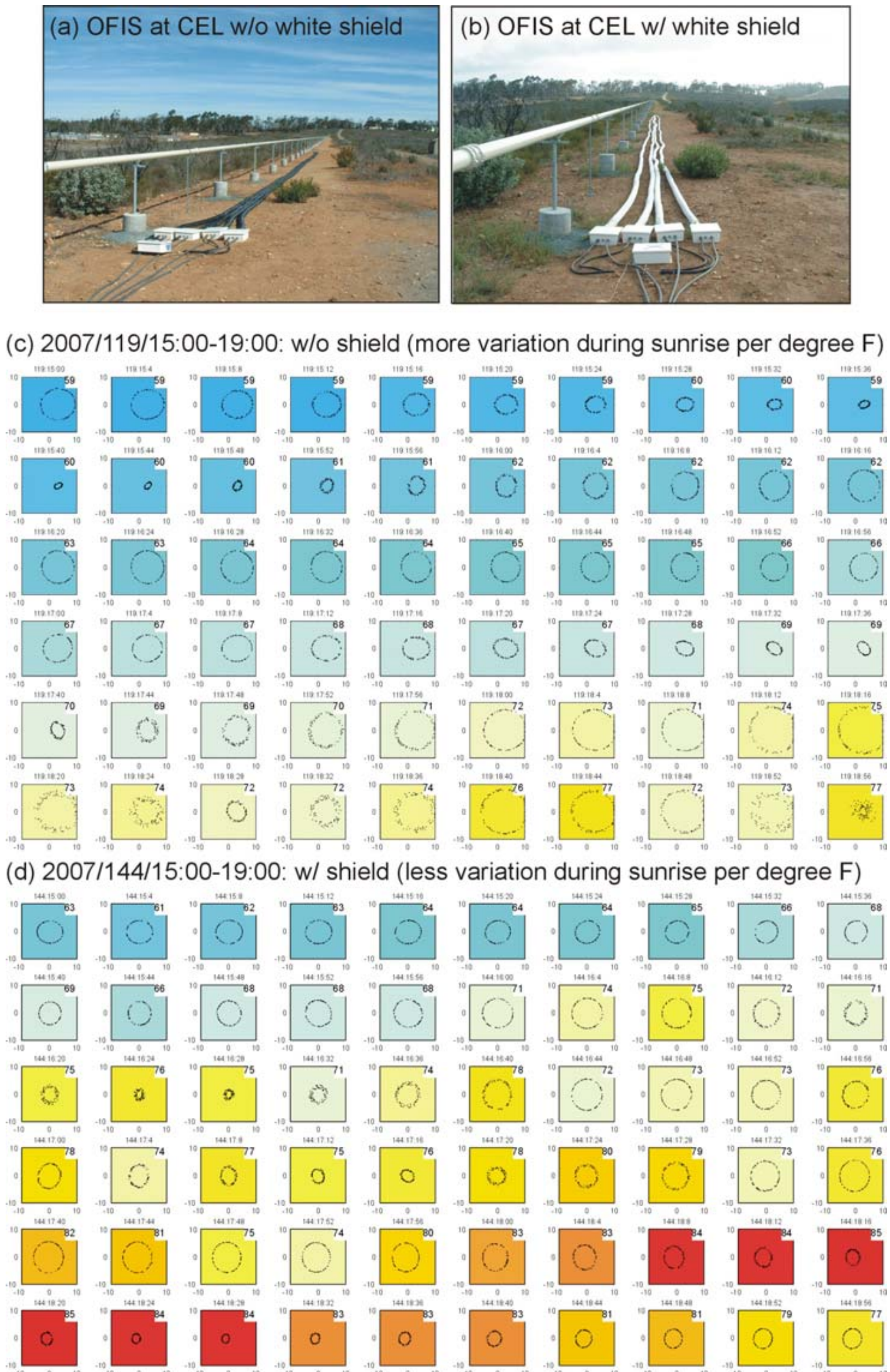


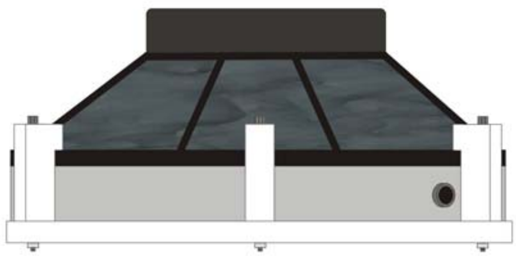
Fig. 5. White shields on the OFIS combat temperature-induced polarization change. The photos were taken on different days than when the ellipse data were recorded.

OFIS Calibration

The OFIS has been carefully calibrated many times in the laboratory and in the field using daytime rocket launch signals. This empirical calibration factor that converts the phase angle along the ellipse to pressure change is about

2.5 Pa-m/rad (Zumberge et al., 2003), where the length unit is the length of the OFIS (the longer OFIS the OFIS, the more sensitive it is).

We recently developed a real-time calibrator to investigate how the sensitivity of the OFIS behaves with respect to changes in outside temperature, inside temperature, when it is wet (raining), and atmospheric pressure (Fig. 6). The calibrator is comprised of a PVC ring that has a speaker sealed to one end, and a plate sealed to the other. A pipe connects the sealed chamber to all the OFIS arms. The speaker is driven by a sinusoid source with a 30 s period. Inside the silicone tube at each OFIS end, a *Setra* differential pressure sensor with a range of +/- 62 Pa records the sinusoid calibrator signal. We apply a narrow bandpass filter to both the Setra and OFIS recordings to obtain the calibration signal amplitude in Pa and radians, respectively. We then can calculate the optimum calibration factor, which we assume is valid at all frequencies based on a previous sweep calibration study that showed the OFIS impulse response was flat in the low-frequency audible sound range.



Specifications

- 500 Watt, 8 inch diameter speaker
- Speaker paper sprayed with sealer
- 1 inch long gray PVC ring
- 1/4 inch white polymer end plate
- Driven by 80 W, 30 s sinusoid source
- Plumbed to all OFIS via 1/4 inch pipe

Fig. 6. OFIS real-time calibrator sketch.

Analyzing a day of data beginning at 18:00 UTC (hour 18, 11 AM local time) in 15-minute time bins for the four OFIS arms at CEL shows that the sensitivity of the OFIS is correlated with outside temperature change. Figure 7a shows the amplitude of the calibration signal as recorded by the OFIS arms and associated Setras. The OFIS amplitudes are converted to pressure using the constant, previously estimated OFIS calibration factors to facilitate ease of comparison. If the calibration factors were correct, the Setra and OFIS amplitudes would be identical. Instead, the OFIS amplitudes vary throughout the day with temperature (Fig. 7b) and get smaller at night beginning at hour 27 (7 PM local time). Viewed in another way, the corrected calibration factors for each OFIS (Fib. 7c) show that the OFIS is more sensitive than previously thought when the temperature is above 80º F, but less sensitive when the temperature dips at night. It is unclear why OFIS 3 and 4 respond differently to the temperature change than OFIS 1 and 2.

The sensitivity of the OFIS varies linearly with temperature between 60-80º F (Fig. 7d). In this figure, the calibration factor for OFIS 1 is plotted with respect to temperature. The factor lags the temperature change as expected due to the effect of the heat capacity and the insulation surrounding the silicone tube. However, another experiment spanning a larger temperature range showed that at temperatures below 60º F, the calibration factor rises much more rapidly. Above 80º F, all the factors appear to converge to ~2.0 Pa-m/rad. Therefore for the broader range of temperatures, the relationship is non-linear.

There is a rapid buildup of pressure inside the OFIS during periods of temperature change. Although we dissipate most of this buildup using peek tubes of certain lengths, we determined that pressure buildup inside the OFIS is not related to the sensitivity simply by venting one OFIS at night and not observing any change in the real-time acoustic noise amplitude. We also compressed one OFIS with 1 psi of air for a day and did not see any change in the difference in the amplitudes of the signals when compared with the other OFIS, suggesting that the variation in the calibration is not associated with a variation in the tension of the fiber around the silicone tube (which may occur due to thermal expansion/contraction of the silicone). Our working hypothesis is that the rigidity of the silicone (and sensitivity of the sensor) changes significantly with temperature. However, other observations suggest that there is another factor (possibly in combination with a changing rigidity) that is responsible.

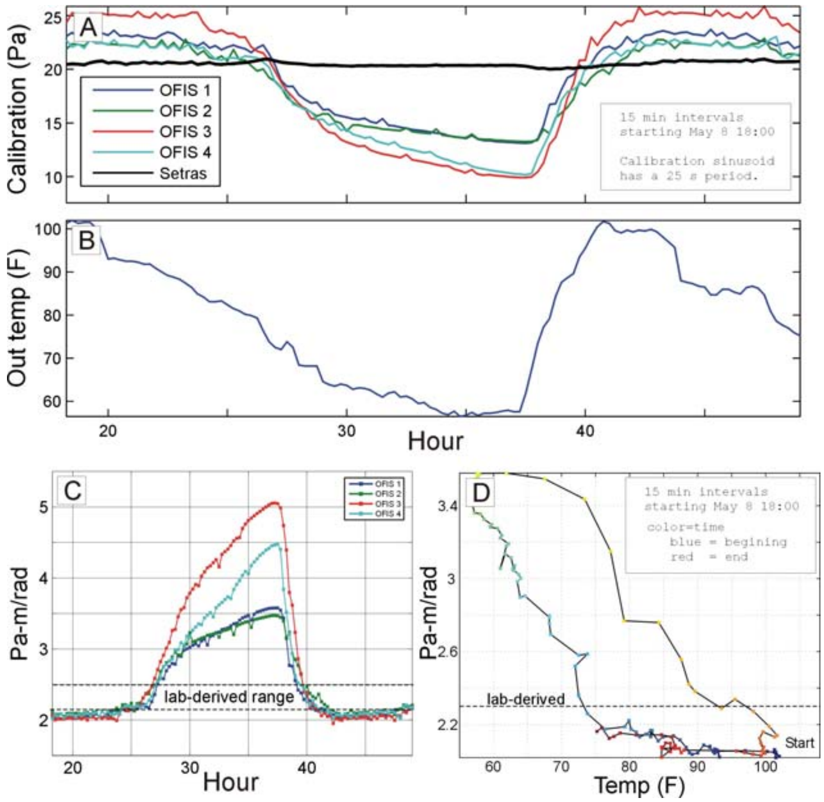


Fig. 7. Calibration results. The OFIS calibration factor (Pa-m/rad) reflects the sensitivity of the OFIS to pressure signals, with larger values indicating lesser sensitivity. The OFIS is most sensitive at temperatures above 85° F.

Coherence of Parallel OFIS

There are several ways to compare the impulse responses of two sensors in the infrasound frequency range. One technique is to put two sensors close together, then calculate and stack coherence functions for recorded background noise in time series X and Y. The coherence is a measure of the similarity (linear relationship) between two signals as a function of frequency. Specifically, it is defined in frequency space as the magnitude of the X/Y cross-correlation complex spectrum divided by the product of the X/Y autocorrelation complex spectra. The magnitude of the coherence is 1 for frequencies where there is a perfect linear relationship across the time window, and 0 at frequencies where there is no relationship. For signals that are identical, but time shifted, the coherence is 1 for all frequencies. Typically a coherence of less than 0.25 indicates that no significant relationship exists.

Three parallel OFIS at CEL were separated by about 4 inches and paired off to form three unique pairs. The magnitude of the coherence functions for these pairs was calculated and stacked in 15 minute bins (Fig. 8). Two sets of data were used. The first set was collected when the 3 parallel OFIS were interconnected via the calibrator plumbing (Fig. 6), which added an additional, shared 100 feet of pipe between the calibrator and the ball valves at the end of the OFIS arms. The second set of data was collected when the 3 OFIS were not interconnected. Because acoustic noise can rise with wind speed, we also stack only those coherence functions for which the median wind speed is greater than or equal to 3 m/s. We see that for most cases, the coherence is above about 0.40. Also, for each case, the coherence increases at frequencies >15-20 Hz for higher wind speeds. Conversely, for frequencies below 15 Hz, the coherence decreases for higher wind speeds. This decrease is especially pronounced for the case where the OFIS arms are interconnected. We speculate that a decrease in coherence in the presence of an increase in wind noise might be related to resonation or mechanical capacitance (for the interconnected case) in the OFIS arms, which vary in length by up to 8 m. In addition, between the calibrator and OFIS arms, there are several acoustic impedance contrasts. The acoustic impedance at the ball valves changes when we open them up, which may also be related to the differences in coherence between case (a) and (b). Finally, these data only span 1 day (Fig. 8b) and 2 days (Fig. 8a), which may not be enough data to be statistically significant. We will repeat this experiment by

truncating the OFIS to the same length, analyzing a week's worth of noise data and several individual signals, applying the corrected calibration factors, stacking the associated power spectral densities for each bin, and calculating the 95% confidence coherence level. If the repeated experiment also suggests an increase in noise from 1-20 Hz when wind speed increases, we will likely modify the calibration system such that it turns on for 30 seconds once every 15 minutes, while opening solenoid valves to each OFIS arm.

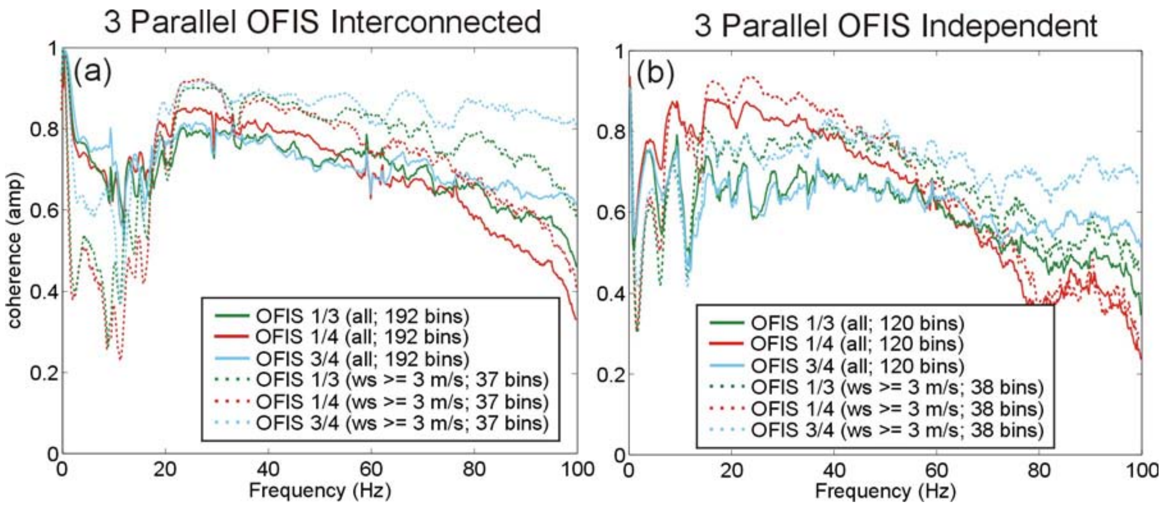


Fig. 8. Coherence of interconnected and independent parallel OFIS (OFIS 1, 3, and4) at CEL.

M-Sequence Calibration Technique

It is difficult to accurately calibrate infrasound sensors because of the difficulty in generating infrasound. Standard subwoofers are designed to have flat impulse responses down to ~20 Hz. Propane cannons or impulsive devices have difficulty generating infrasound in the 1-5 Hz range. We are in the process of experimenting with an array of 12-inch, 500 Watt subwoofers in an attempt to extend the array impulse response into the infrasound band. Since the source is peak power limited, we are using an M-sequence signal, which allows us to increase the SNR by coherent processing and thus to observe distant, low-source power signals recorded over many minutes. With this technique, one can measure the impulse response of each OFIS arm under various wind noise conditions.

An M-sequence is a pseudo-random series of binary digits that has been extensively used in communication and imaging systems during the last 50 years. M-sequences are periodic, and generated with the use of a bit register and feedback law (Golomb, 1967). The period of an M-sequence is $2^N - 1$, where N is the length of the bit register. We then phase modulate a sinusoid of a frequency f_c with the M-sequence digits contolling the phase. For example, we modulated a 50 Hz signal with 255 bit sequence at a chip rate of 2 carrier cycles per digit to get a 10.2 s long signal. We consecutively transmitted 24 of these coded signals to obtain a signal 244.8s long. We process the received signal by correlation with the original signal and then demodulating. We stack these together to enjoy a processing gain of 10*log10(24*255) = 37.9 dB.

This example was implemented at CEL using a single subwoofer placed 270 m from the four OFIS and a B&K microphone with a sponge wind filter. The azimuth from the subwoofer to the OFIS center was 4º from the OFIS perpendicular, which means the signal wavefronts were approximately plane waves that impacted the entire 60-m OFIS and microphone simultaneously. Both sensors were sampled at 200 Hz. The 4-minute long coded signal was impossible to observe by inspection in the 1 Hz high-passed B&K microphone time series, but is observed with a visual signal-to-noise ratio of 5 dB in the OFIS recording (Fig. 9a). The spectrograms for both sensors show that the signal was observed. The demodulated signal peak corresponding to the first arrival has a signal to noise ratio of 34 dB for the B&K, and 46 dB for the OFIS (Fig. 4d), which confirms that a 60-m OFIS is exceptionally sensitive to low-frequency sound and attenuates well wind noise and other sources of low-frequency sound that come from different directions that are not perpendicular to the length of the OFIS.

One application of this technique is to analyze each of the 24 coded signals separately and to measure the demodulated power and travel time of these signals. Since we hold the power input into the subwoofer constant

(~120 Watts), any demodulated power or travel time fluctuations result from a change in the impulse response of the medium. Therefore one can measure the coherence time of the atmosphere or changes in the velocity profile with time. We find a considerable degree of variability in the demodulated B&K signal power (Fig. 9e), and a more smooth variability for the OFIS recordings (Fig. 9f), suggesting that the array gain of the OFIS effectively averages fluctuations in the Green's function. We performed the same experiment at f_c = 20, 10, 5, and 1 Hz. We only observed the coded signal for the 50 and 20 Hz cases, running into the expected subwoofer roll-off at sub-audible frequencies.

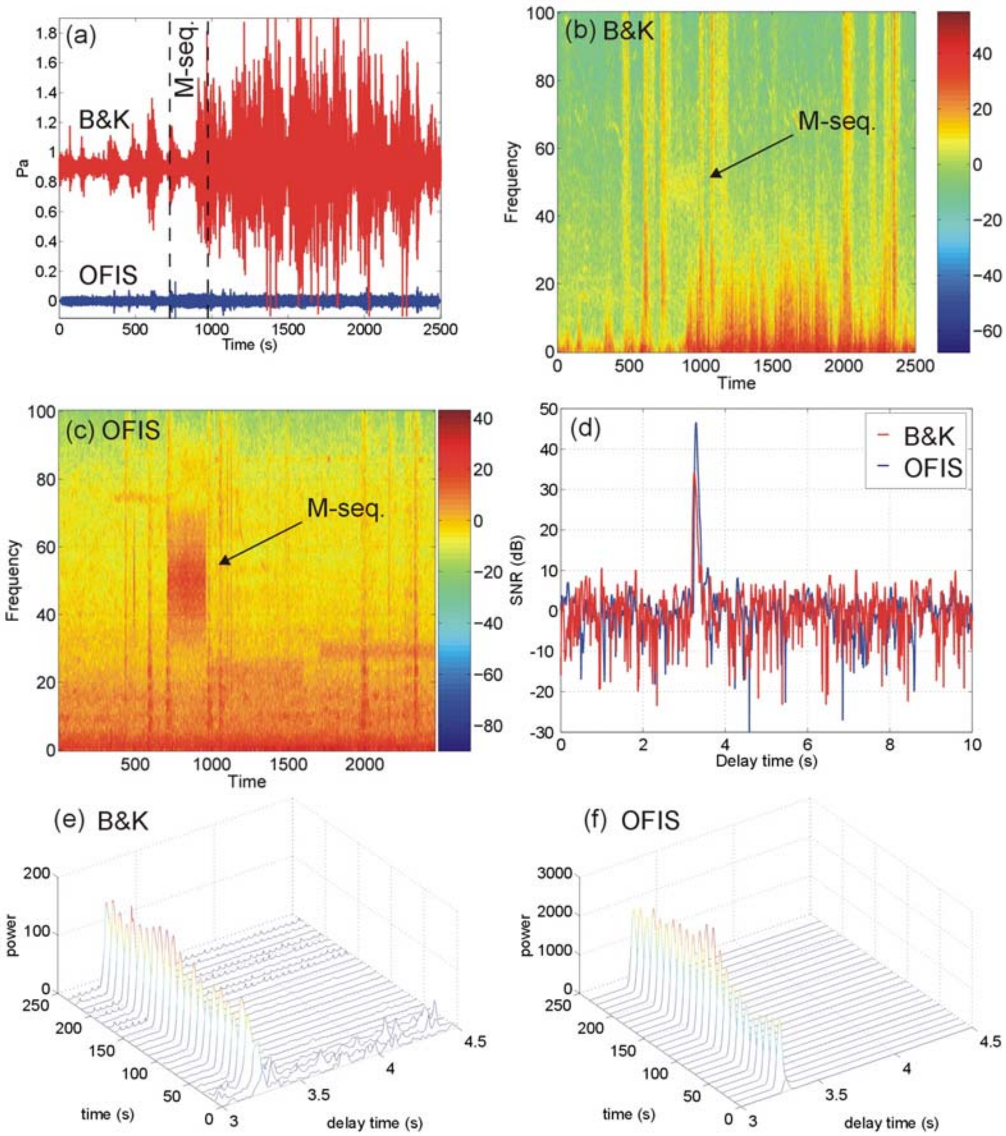


Fig. 9. M-sequence calibration technique using a 12-inch subwoofer at 270 m distance from a tuned OFIS and a Brüel & Kjær (B&K) microphone with sponge wind filter.

Real-Time Infrasonic Radar

Previous PFO OFIS studies showed significant deviations at times between the back azimuths determined by an OFIS and a microbarometer array. Although a 2006 WSMR II rocket explosion provided a good signal that proved the OFIS could be more accurate than the co-located Chaparral sensor array (presumably in this case because of handheld GPS inaccuracies in locating the array element positions or problems with moisture in the porous hoses connected to the Chaparrals or in the Chaparrals themselves), it is generally ambiguous as to the more accurate

technique since the true signal back azimuths are not usually known. The six-arm OFIS at CEL (Fig. 3) will test various OFIS configurations and phase velocity direction determination by exposing the OFIS array to a number of infrasound sources (slowly moving aircraft) that can be confirmed via video. This is expected to eliminate any ambiguities.

The obstacles in this research were the OFIS arm preparations (resulting in the findings reported above), the Camp Elliott site preparation, and the migration of the OFIS data logging software from an in-house format running on Windows XP to an industrial-strength streaming format (analogous to the CD1.1 format) running on a more secure and less problematic UNIX machine. We have installed a video camera and confirmed that we can easily make out moving sources across the sky (http://sail.ucsd.edu/~walker/c130_landing.mov). What remains to be done now is to route data from the video camera and OFIS DSP's into a program that analyzes the OFIS data and creates a radar plot in near real time, and compare between the video display and the OFIS radar display.

CONCLUSIONS AND RECOMMENDATIONS

The sensitivity of the OFIS is temperature dependent. Fortunately the first order sensitivity level of the OFIS is still far above the threshold such that it can accurately detect and accurately record infrasound signals throughout the normal daily temperature fluctuation. Therefore, the real-time speaker calibrator that we developed provides a means to compensate for this sensitivity variation assuming the recorded background noise is acoustic in nature.

Preliminary evidence suggests that the coherence of adjacent, parallel OFIS arms varies from 1.0 down to 0.4. In higher wind conditions, the coherence goes down significantly in the 1-20 Hz band if the newly developed speaker calibrator system is being implemented. More data processing is necessary to confirm this finding and understand why it happens.

White mesh shields provide a good level of protection against rapid temperature change of the sensor, which leads to polarization change that negatively impacts the size and geometry of the ellipse and can reduce uptime of the OFIS sensor by up to ~10%. In addition, trimming the differential fiber length of the two fibers wrapped around the OFIS to within 2 inches eliminates optical noise associated with the coherence time of the laser we use, which improves the definition of the ellipse.

M-sequences can be used to drive weak sources of infrasound to develop a calibration tool. The concept was demonstrated in the audible band with a 20 and 50 Hz signal, which showed that a 60-m OFIS attenuated wind and other undesirable noise by 12 dB more than that provided by a standard B&K microphone with attached sponge wind filter. It remains to be seen if an array of subwoofers can conspire with M-sequences to form such an infrasound sensor calibrator.

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